# EVALUATION ON PERFORMANCE OF SQUARE FINNED CONFORMAL COOLING CHANNEL (SFCCC) FABRICATED BY SELECTIVE LASER MELTING (SLM) ON PLASTIC MOULDED PART

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Special dedication to my beloved parents, wife and family..... Thanks for the love, support and memories

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## ABSTRACT

In plastic injection moulding (PIM) process, the cooling stage is the most important phase because it significantly affects the productivity and quality of the molded part. Thus, the cooling system need to be emphasized in designing the injection mould system. The application of conformal cooling channels which only can be fabricated by additive manufacturing technology (AM) are proven to increase the injection moulding performance and able to reduce the quality issues. This research introduced the Square Finned Conformal Cooling Channel (SFCCC) in the PIM as a way to enhance the performance of square shape conformal cooling channel (SSCCC) in PIM. The mould insert with SFCCC has been designed, simulated via finite element analysis software, fabricated (by combination of High Speed Machining and Selective Laser Melting (SLM)), and tested using a front panel housing as the injected part for the case study. Eight types of variate SFCCC design (SFCCC 1 to SFCCC 8) employing finned and sub groove concept were analysed via simulation work to determine the best design in terms of shortest cooling time. The results showed that the shortest cooling time recorded by SFCCC 8 was at 7.621 sec, an improvement of 16.44% compared with SSCCC. In terms of cycle time, the SFCCC is able to improve the SSCCC by 8.33% to 10.26%. Meanwhile, in comparison with industrial mould using Milled Groove Conformal Cooling Channel (MGCCC), the SFCCC showed an improvement of 19.60% to 39.36% based on the coolant temperature. The experimental results showed the greatest shrinkage in the X-direction at 0.93% and the smallest shrinkage at 0.6%. For the Y-direction, the greatest shrinkage is 0.97% and the smallest shrinkage is 0.39%. In comparison with the injected part via MGCCC, the SFCCC had a slightly greater overall shrinkage in relation to the shrinkage and warpage at points X and Y direction. Most front panel housing shrinkage and warpage values in the experimental study were smaller than those of the simulative study. However, the experimental results were in line with the simulative results, proving that the SFCCC design had better cycle times and acceptable quality for an industrial mould.

## ABSTRAK

Dalam proses pengacuan suntikan plastik (PIM), penyejukan merupakan fasa yang paling penting kerana ianya memberi kesan yang signifikan kepada produktiviti dan kualiti terhadap komponen yang dihasilkan. Dengan itu, tumpuan yang lebih perlu diberikan dalam merekabentuk sesebuah pengacuan suntikan. Penggunaan saluran penyejukan konformal (yang hanya boleh dihasilkan dengan menggunakan teknologi aditif (AM)) telah terbukti dapat meningkatkan prestasi proses pengacuan suntikan dan seterusnya mampu mengurangkan isu-isu berkaitan dengan kualiti. Kajian ini telah memperkenalkan penggunaan saluran penyejukan konformal bersirip berbentuk segiempat (SFCCC) di dalam proses pengacuan suntikan (PIM) yang bertujuan untuk meningkatkan prestasi saluran penyejukan konformal berbentuk segiempat (SSCCC). Acuan suntikan dengan SFCCC telah direkabentuk, disimulasi dengan perisian kaedah analisis terhingga, dihasilkan (dengan menggunakan pemesinan berkelajuan tinggi (HSM) dan pencairan laser terpilih (SLM)) dan diujilari dengan menggunakan panel perumah hadapan sebagai produk untuk kajian kes. Lapan jenis rekabentuk SFCCC yang berbeza (SFCCC 1 hingga SFCCC 8) menggunakan konsep sirip dan lurah kecil telah dianalisis dengan menggunakan simulasi bagi menentukan rekabentuk terbaik dengan mengambil kira masa penyejukan yang paling pendek. Dengan penentuan suhu penyejuk antara 25ºC to 60ºC, SFCCC 8 mencatatkan keputusan masa penyejukan paling pendek iaitu 7.621 saat dengan penambahbaikan sebanyak 16.44% berbanding dengan SSCCC. Untuk kitaran masa, SFCCC telah meningkatkan prestasi SSCCC di antara 8.33% hingga 10.26%. Sementara itu, perbandingan antara acuan industri yang menggunakan penyejukan konformal berbentuk segiempat alur terkisar (MGCCC) dengan acuan suntikan SFCCC pula telah menunjukkan peningkatan sebanyak 19.6% hingga 39.36% bergantung kepada suhu penyejuk. Keputusan ujikaji menunjukkan pengecutan yang paling besar berlaku pada arah-X bernilai 0.93% dan nilai paling kecil pula adalah sebanyak 0.6%. Untuk arah – Y pula, nilai pengecutan paling besar

berjumlah 0.97% dan nilai terkecil adalah sebanyak 0.39%. Perbandingan pada nilai keseluruhan bagi pengecutan dan ledingan pada komponen yang disuntik menunjukkan nilai bagi SFCCC lebih besar berbanding dengan MGCCC pada kedua-dua arah x dan y. Manakala hampir kesemua nilai pengecutan dan ledingan bagi ujikaji lebih kecil berbanding dengan nilai dari simulasi. Walaubagaimanapun keputusan ujikaji adalah selari dengan keputusan simulasi, ini membuktikan bahawa rekabentuk SFCCC mempunyai nilai kitaran masa yang lebih singkat namun tidak menjejaskan kualiti komponen yang dihasilkan.

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## LIST OF SYMBOLS AND ABBREVIATIONS

| | | |
|---|---|---|
| ABS | - | Acrylonitrile Butadiene Styrene |
| AM | - | Additive Manufacturing |
| ANN | - | Artificial Neural Network |
| ANSYS | - | Analysis System |
| CAD | - | Computer Aided Design |
| CAE | - | Computer Aided Engineering |
| CMM | - | Coordinate Measuring Machine |
| CNC | - | Computer Numerical Control |
| DMLS | - | Direct Metal Laser Sintering |
| DMT | - | Direct Metal Tooling |
| EDM | - | Electro Discharged Machining |
| FEA | - | Finite Element Analysis |
| FEM | - | Finite Element Method |
| GA | - | General Algorithm |
| MFI | - | MoldFlow Insight |
| MGCCC | - | Milled Groove Square-shaped Conformal Cooling Channel |
| MGSS | - | Milled Grooved Square Shape |
| PC | - | Polycarbonate |
| PIM | - | Plastic Injection Moulding |
| POM | - | Polyoxymethylene |
| PP | - | Polypropylene |
| RP | - | Rapid Prototyping |
| RT | - | Rapid Tooling |
| SFCCC | - | Square Finned Conformal Cooling Channels |

| | | |
|---|---|---|
| SLM | - | Selective Laser Melting |
| SLS | - | Selective Laser Sintering |
| SSCCC | - | Square Shape Conformal Cooling Channels |
| VRCCC | - | Variable Radius Conformal Cooling Channel |
| STL | - | Stereolithography |
| 3DP | - | Three Dimensional Printing |
| $L_{cavity}$ | - | Cavity length |
| $p$ | - | Wetted perimeter of the cooling channels |
| $\mu$ | - | Dynamic viscosity of water |
| A | - | Cross-sectional area of the cooling channels |
| $D_H$ | - | Hydraulic diameter |
| $L_{part.}$ | - | Part length |
| $Q_{molding}$ | - | Quantity of heat dissipated by the cooling system |
| $m_{molding}$ | - | Mass of the moulded part |
| $C_p$ | - | Specific heat of injected part |
| $T_{melt}$ | - | Melting temperature |
| $T_{eject}$ | - | Ejection temperature |
| $V_{mf}$ | - | Volume of the injected part |
| $\rho$ | - | Density of the plastic material |
| $\dot{Q}_{cooling}$ | - | Cooling power |
| $t_c$ | - | Cooling time of runner |
| $\alpha$ | - | Thermal diffusivity |
| $T_{coolant}$ | - | Coolant temperature |
| $\dot{Q}_{line}$ | - | Heat transfer rate per cooling line |
| $n_{lines}$ | - | Number of cooling lines |
| $\dot{V}_{coolant}$ | - | Coolant flow rate |
| $\Delta$ | - | Difference |
| $D_{max}$ | - | Maximum size of the cooling channel |
| $R_e$ | - | Reynolds number |
| $H_{line}$ | - | Distance from cooling channel to mould surface |
| $\emptyset$ | - | Diameter |
| $K$ | - | Thermal conductivity |

| | | |
|---|---|---|
| $\sigma_{endurance}$ | - | Stress endurance |
| $\sigma_{nominal}$ | - | Nominal compressive stress |
| $Pr$ | - | Prandtl number |
| sec | - | Second |
| mm | - | Millimeter |
| $Nm^{-2}$ | - | Newton / meter square |
| $cm^3$ | - | Centimeter cubic |
| kg/hr | - | Kilogram per hour |

# REFERENCES


Aboulkhair, N. T., Everitt, N. M., Ashcroft, I., & Tuck, C. (2014). Reducing porosity in AlSi10Mg parts processed by selective laser melting. *Additive Manufacturing*, *1–4*, 77–86.

Agyenim, F., Eames, P., & Smyth, M. (2009). A comparison of heat transfer enhancement in a medium temperature thermal energy storage heat exchanger using fins. *Solar Energy*, *83*, 1509–1520.

Ahn, D. G., & Kim, H. W. (2010). Study on the manufacture of a thermal management mould with three different materials using a direct metal tooling rapid tooling process. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, *224*, 385–402.

Ahn, D. G., Park, S. H., & Kim, H. S. (2010). Manufacture of an Injection Mould with Rapid and Uniform Cooling Characteristics for the Fan Parts Using a DMT Process. *International Journal of Precision Engineering and Manufacturing*, *11*, 915–924.

Airbus, S. (2014). Printing the future: airbus expands its applications of the revolutionary additive layer manufacturing process. *Release-Detail/Detail/Printing-the-Future-Airbus-Expands.*

Al-Abidi, A. A., Mat, S., Sopian, K., Sulaiman, M. Y., & Mohammad, A. T. (2014). Experimental study of melting and solidification of PCM in a triplex tube heat exchanger with fins. *Energy and Buildings*, *68*, 33–41.

Alamgholilou, A., & Esmaeilzadeh, E. (2012). Experimental investigation on hydrodynamics and heat transfer of fluid flow into channel for cooling of rectangular ribs by passive and EHD active enhancement methods. *Experimental Thermal and Fluid Science*. doi:10.1016/j.expthermflusci.2011.11.008

Ali, M. H., & Shuaibu, B. (2017). Design of horizontal fin array for radiative heat transfer, *020014*, 020014.

Altaf, K., Raghavan, V. R., & Rani, A. M. A. (2011). Comparative thermal analysis of circular and profiled cooling channels for injection mold tools. *Journal of Applied Sciences*, *11*, 2068–2071.

Altaf, K. (2011). *Novel Techniques for Reducing Cooling Time in Polymer Injection Moulds using Rapid Tooling Technologies*. UNIVERSITI TEKNOLOGI PETRONAS.

Altaf, K., Majdi Abdul Rani, A., & Raghavan, V. R. (2013). Prototype production and experimental analysis for circular and profiled conformal cooling channels in aluminium filled epoxy injection mould tools. *Rapid Prototyping Journal*, *19*, 220–229.

Altaf, K., Rani, A. M. A., & Raghavan, V. R. (2011). Fabrication of circular and Profiled Conformal Cooling Channels in aluminum filled epoxy injection mould tools. *2011 National Postgraduate Conference - Energy and Sustainability: Exploring the Innovative Minds, NPC 2011*, 1–4.

Altan, M. (2010). Reducing shrinkage in injection moldings via the Taguchi, ANOVA and neural network methods. *Materials and Design*. doi:10.1016/j.matdes.2009.06.049

Amran, M., Salmah, S., Izamshah, R., Shahir, M., Amri, M., Mohamad, E., … Musa, M. K. (2015). Warpage Analysis of Different Number Cooling Channels for Dumbbell Plastic Part in Injection Moulding. In *Applied Mechanics and Materials* (Vol. 761, pp. 8–11). Trans Tech Publ.

Annicchiarico, D., & Alcock, J. R. (2014a). Review of factors that affect shrinkage of molded part in injection molding. *Materials and Manufacturing Processes*. doi:10.1080/10426914.2014.880467

Annicchiarico, D., & Alcock, J. R. (2014b). Review of Factors that Affect Shrinkage of Molded Part in Injection Molding. *Materials and Manufacturing Processes*, *29*, 662–682.

Armillotta, A., Baraggi, R., & Fasoli, S. (2014). SLM tooling for die casting with conformal cooling channels. *International Journal of Advanced Manufacturing Technology*, *71*, 573–583.

Au, K. (2009). *Conformal cooling channels design for rapid plastic injection mould*. The Hong Kong Polytechnic University.

Au, K. M., & Yu, K. M. (2007). A scaffolding architecture for conformal cooling design in rapid plastic injection moulding. *The International Journal of Advanced Manufacturing Technology*, *34*, 496–515.

Au, K. M., & Yu, K. M. (2014). Variable Radius Conformal Cooling Channel for Rapid Tool. *Journal of Manufacturing Science and Engineering*, *136*, 044501.

Azdast, T., & Behravesh, A. H. (2008). An Analytical Study of Constrained Shrinkage of Injection Molded Semi-Crystalline Plastic Parts. *Polymer-Plastics Technology and Engineering*, *47*, 1265–1272.

Brandl, E., Heckenberger, U., Holzinger, V., & Buchbinder, D. (2012). Additive manufactured AlSi10Mg samples using Selective Laser Melting (SLM): Microstructure, high cycle fatigue, and fracture behavior. *Materials & Design*, *34*, 159–169.

Brandt, M., Sun, S., Leary, M., Feih, S., Elambasseril, J., & Liu, Q. (2013). High-Value SLM Aerospace Components: From Design to Manufacture. *Advances in Engineering Materials, Product and Systems Design*, *633*, 135–147.

British Standards Institute. (2008). *BS EN ISO 291: Plastics - Standard atmospheres for conditioning and testing*. *International Standard* (Vol. 3).

Buchbinder, D., Schleifenbaum, H., Heidrich, S., Meiners, W., & Bültmann, J. (2011). High Power Selective Laser Melting (HP SLM) of Aluminum Parts. *Physics Procedia*, *12*, *Part A*, 271–278.

Calignano, F. (2014). Design optimization of supports for overhanging structures in aluminum and titanium alloys by selective laser melting. *Materials & Design*, *64*, 203–213.

Çengel, Y. A. (2007). *Heat and Mass Transfer: A Practical Approach, Third Edition*

(Thirrd Edt).

Chen, C.-C. A., & Chang, S.-W. (2008). Shrinkage Analysis on Convex Shellby Injection Molding. *International Polymer Processing*, *23*, 65–71.

Chen, C. C., Su, P. L., & Lin, Y. C. (2009). Analysis and modeling of effective parameters for dimension shrinkage variation of injection molded part with thin shell feature using response surface methodology. *International Journal of Advanced Manufacturing Technology*, *45*, 1087–1095.

Chen, W.-C., Fu, G.-L., Tai, P.-H., & Deng, W.-J. (2009). Process parameter optimization for MIMO plastic injection molding via soft computing. *Expert Systems with Applications*, *36*, 1114–1122.

Chen, X., Lam, Y. C., & Li, D. Q. (2000). Analysis of thermal residual stress in plastic injection molding. *Journal of Materials Processing Technology*, *101*, 275–280.

Chiang, K. T., & Chang, F. P. (2007). Analysis of shrinkage and warpage in an injection-molded part with a thin shell feature using the response surface methodology. *International Journal of Advanced Manufacturing Technology*. doi:10.1007/s00170-006-0739-4

Dang, X.-P., & Park, H.-S. (2011). Design of U-shape milled groove conformal cooling channels for plastic injection mold. *International Journal of Precision Engineering and Manufacturing*, *12*, 73–84.

Dang, X. P., & Park, H. S. (2011). Design of u-shape milled groove conformal cooling channels for plastic injection mold. *International Journal of Precision Engineering and Manufacturing*, *12*, 73–84.

Dangayach, G. S., & Kumar, D. (2012). Reduction in Defect Rate by Taguchi Method in Plastic Injection Molded Components. *Advanced Materials Research*. doi:10.4028/www.scientific.net/AMR.488-489.269

Das, S., Hollister, S. J., Flanagan, C., Adewunmi, a, Bark, K., Chen, C., … Widjaja, E. (2003). Freeform fabrication of Nylon-6 tissue engineering scaffolds. *Rapid Prototyping Journal*, *9*, 43–49.

Dastagiri, M., & Prasad, M. M. (2010). Application of axiomatic design in injection molding process. In *Frontiers in Automobile and Mechanical Engineering (FAME), 2010* (pp. 222–228).

De Santis, F., Pantani, R., Speranza, V., & Titomanlio, G. (2010). Analysis of shrinkage development of a semicrystalline polymer during injection molding. *Industrial and Engineering Chemistry Research*. doi:10.1021/ie901316p

Dolinšek, S. (2005). Wear characteristics of laser sintered molding tools. *Wear*, *259*, 1241–1247.

Dominick V. Rosato, Rosato, D. V., & Rosato, M. G. (2000). *Injection molding handbook*. Springer Science & Business Media.

Elshafei, E. A. M., Safwat Mohamed, M., Mansour, H., & Sakr, M. (2008). Experimental study of heat transfer in pulsating turbulent flow in a pipe. *International Journal of Heat and Fluid Flow*.

Erzurumlu, T., & Ozcelik, B. (2006). Minimization of warpage and sink index in injection-molded thermoplastic parts using Taguchi optimization method. *Materials and Design*, *27*, 853–861.

Fang, Z., Starly, B., & Sun, W. (2005). Computer-aided characterization for effective mechanical properties of porous tissue scaffolds. *CAD Computer Aided Design*, *37*, 65–72.

Fernandes, C., Pontes, A. J., Viana, J. C., & Gaspar-Cunha, A. (2010). Using multiobjective evolutionary algorithms in the optimization of operating conditions of polymer injection molding. *Polymer Engineering and Science*.

Ferreira, J. C., & Mateus, A. (2003). Studies of rapid soft tooling with conformal cooling channels for plastic injection moulding. *Journal of Materials Processing Technology*, *142*, 508–516.

Fischer, J. M. (2012a). *Handbook of Molded Part Shrinkage and Warpage: Second Edition*. *Handbook of Molded Part Shrinkage and Warpage: Second Edition*.

Fischer, J. M. (2012b). *Handbook of Molded Part Shrinkage and Warpage: Second Edition*. *Handbook of Molded Part Shrinkage and Warpage: Second Edition*.

Gopakumar, T. (2017). No Title. Retrieved from http://www.kicoto.com/VdZNZ/food-ingredients.html

Gorman, J. M., Krautbauer, K. R., & Sparrow, E. M. (2016). Thermal and fluid flow first-principles numerical design of an enhanced double pipe heat exchanger. *Applied Thermal Engineering*, *107*, 194–206.

Hassan, H., Regnier, N., Le Bot, C., & Defaye, G. (2010). 3D study of cooling system effect on the heat transfer during polymer injection molding. *International Journal of Thermal Sciences*, *49*, 161–169.

Hearunyakij, M., Sontikaew, S., & Sriprapai, D. (2014). Improvement in the Cooling Performance of Conformal Mold Cooling By Using Fin Concept. *International Journal of Mining, Metallurgy & Mechanical Engineering*, *2*, 41–46.

Hopmann, C., & Fischer, T. (2015). New plasticising process for increased precision and reduced residence times in injection moulding of micro parts. *CIRP Journal of Manufacturing Science and Technology*, *9*, 51–56.

Huang, G., Li, X., Wu, X., & Li, J. (2009). Optimized Design of Injection Mould for Mobile Phone Front Shell Based on CAE Technology. In *Artificial Intelligence, 2009. JCAI '09. International Joint Conference on* (pp. 648–650).

Huang, M., & Tai, C. (2001). The effective factors in the warpage problem of an injection-molded part with a thin shell feature. *Journal of Materials Processing Technology*.

Ilyas, I., Taylor, C., Dalgarno, K., & Gosden, J. (2010). Design and manufacture of injection mould tool inserts produced using indirect SLS and machining processes. *Rapid Prototyping Journal*, *16*, 429–440.

Jansen, K. M. B., Pantani, R., & Titomanlio, G. (1998). As-molded shrinkage measurements on polystyrene injection molded products. *Polymer Engineering and Science*.

Kalita, S. J., Bose, S., Hosick, H. L., & Bandyopadhyay, A. (2003). Development of controlled porosity polymer-ceramic composite scaffolds via fused deposition modeling. *Materials Science and Engineering C*, *23*, 611–620.

Kazmer, D. (2007). *Injection Mold Design Engineering*.

Kazmer, D. O. (2012). *Injection mold design engineering*. Carl Hanser Verlag GmbH Co KG.

Kemal Karasu, M., Cakmakci, M., Cakiroglu, M. B., Ayva, E., & Demirel-Ortabas, N. (2014). Improvement of changeover times via Taguchi empowered SMED/case study on injection molding production. *Measurement: Journal of the International Measurement Confederation*, *47*, 741–748.

Khan, M., Afaq, S. K., Khan, N. U., & Ahmad, S. (2014). Cycle time reduction in injection molding process by selection of robust cooling channel design. *ISRN Mechanical Engineering*, *2014*.

Khan, M., Afaq, S. K., Khan, N. U., & Ahmad, S. (2014). Cycle Time Reduction in Injection Molding Process by Selection of Robust Cooling Channel Design. *International Scholarly Research Notices*, *2014*.

Khondker, O. A., Yang, X., Usui, N., & Hamada, H. (2006). Mechanical properties of textile-inserted PP/PP knitted composites using injection-compression molding. *Composites Part A: Applied Science and Manufacturing*, *37*, 2285–2299.

King, D., & Tansey, T. (2003). Rapid tooling: selective laser sintering injection tooling. *Journal of Materials Processing Technology*, *132*, 42–48.

Kitayama, S., Miyakawa, H., Takano, M., & Aiba, S. (2016). Multi-objective optimization of injection molding process parameters for short cycle time and warpage reduction using conformal cooling channel. *International Journal of Advanced Manufacturing Technology*, 1–10.

Kitayama, S., Onuki, R., & Yamazaki, K. (2014). Warpage reduction with variable pressure profile in plastic injection molding via sequential approximate optimization. *International Journal of Advanced Manufacturing Technology*, *72*, 827–838.

Kramschuster, A., Cavitt, R., Ermer, D., Chen, Z., & Turng, L. (2005). Quantitative study of shrinkage and warpage behavior for microcellular and conventional injection molding. *Polymer Engineering & Science*, *45*, 1408–1418.

Kruth, J., Badrossamay, M., Yasa, E., Deckers, J., Thijs, L., & Humbeeck, J. Van.

(2010). Part and material properties in selective laser melting of metals. *16th International Symposium on Electromachining*, 1–12.

Kruth, J., Mercelis, P., Van Vaerenbergh, J., Froyen, L., & Rombouts, M. (2005). Binding mechanisms in selective laser sintering and selective laser melting. *Rapid Prototyping Journal*, *11*, 26–36.

Kruth, J., Vandenbroucke, B., Vaerenbergh, J., & Mercelis, P. (2005). Benchmarking of different SLS/SLM processes as rapid manufacturing techniques. *Int. Conf. Polymers & Moulds Innovations (PMI), Gent, Belgium, April 20-23, 2005*, 1–7.

Kuo, C., Chen, W., Zhang, J., & Tsai, D. (2017). A new method of manufacturing a rapid tooling with different cross-sectional cooling channels.

Kurtaran, H., Ozcelik, B., & Erzurumlu, T. (2005). Warpage optimization of a bus ceiling lamp base using neural network model and genetic algorithm. *Journal of Materials Processing Technology*, *169*, 314–319.

Lal, P., & Sun, W. (2004). Computer modeling approach for microsphere-packed bone scaffold. *CAD Computer Aided Design*, *36*, 487–497.

Lam, C. X. F., Mo, X. M., Teoh, S. H., & Hutmacher, D. W. (2002). Scaffold development using 3D printing with a starch-based polymer. *Materials Science and Engineering C*, *20*, 49–56.

Laoui, T., Santos, E., & Osakada, K. (2004). Properties of Titanium Implant Models Made By Laser Processing. *Laser Assisted Net Shape Engineering 4 Proceedings of the LANE*, *220*, 475–484.

Leo, V., & Cuvelliez, C. (1996). The effect of the packing parameters, gate geometry, and mold elasticity on the final dimensions of a molded part. *Polymer Engineering and Science*.

Li, C. L. (2001). A feature-based approach to injection mould cooling system design. *CAD Computer Aided Design*, *33*, 1073–1090.

Liao, S. J., Chang, D. Y., Chen, H. J., Tsou, L. S., Ho, J. R., Yau, H. T., … Su, Y. C. (2004). Optimal process conditions of shrinkage and warpage of thin-wall parts. *Polymer Engineering and Science*, *44*, 917–928.

Liebenberg, L., & Meyer, J. P. (2007). In-tube passive heat transfer enhancement in the process industry. *Applied Thermal Engineering*, *27*, 2713–2726.

Lin, C., Wirtz, T., & LaMarca, F. (2007). Structural and mechanical evaluations of a topology optimized titanium interbody fusion cage fabricated by selective laser melting process. *Journal of Biomedical*.

Lin, J. C. (2002). Optimum cooling system design of a free-form injection mold using an abductive network. *Journal of Materials Processing Technology*, *120*, 226–236.

Lin, Z.-C., & Chou, M.-H. (2002). Design of the cooling channels in nonrectangular plastic flat injection mold. *Journal of Manufacturing Systems*, *21*, 167–186.

Liu, C., & Manzione, L. T. (1996). Process Studies in Precision Injection Molding. I: Process Parameters and Precision C. *Polymer Engineering and Science*.

Liu, S., & Sakr, M. (2013). A comprehensive review on passive heat transfer enhancements in pipe exchangers. *Renewable and Sustainable Energy Reviews*, *19*, 64–81.

M Sepe Plastics Technology, & 2013. (n.d.). Dimensional stability after molding: Part 1. *Bill Communications, Inc.*

Mamat, A., Trochu, T. F., & Sanschagrin, B. (1995). Analysis of shrinkage by dual kriging for filled and unfilled polypropylene molded parts. *Polymer Engineering & Science*.

Manfredi, D., Calignano, F., Krishnan, M., Canali, R., Ambrosio, E. P., & Atzeni, E. (2013). From powders to dense metal parts: Characterization of a commercial alsimg alloy processed through direct metal laser sintering. *Materials*, *6*.

Manufacturing, A. (2016). 3D printed titanium alloy could replace bone. *Metal Powder Report*, *71*, 288–289.

Mathivanan, D., & Parthasarathy, N. S. (2009). *Sink-mark minimization in injection molding through response surface regression modeling and genetic algorithm*. (Framingham, Ed.), *International Journal of Advanced Manufacturing Technology* (1st ed, Vol. 45). Massachusetts, USA: Hanser.

Mayer, S. (2009). Optimised mould temperature control procedure using DMLS. *EOS Whitepaper*, 1–11.

Meha, D., Avdiu, A., Krasniqi, F., Muriqi, A., & Berisha, X. (2017). Experimental Analysis of Performance of Heat Exchanger with Plate Fins and Parallel Flow of Working Fluids. *World Journal of Engineering and Technology*, *05*, 435–444.

Mehat, N. M., Kamaruddin, S., & Othman, A. R. (2013). Modeling and Analysis of Injection Moulding Process Parameters for Plastic Gear Industry Application. *ISRN Industrial Engineering*, *2013*, 1–10.

Mercelis, P., & Kruth, J. (2006). Residual stresses in selective laser sintering and selective laser melting. *Rapid Prototyping Journal*, *12*, 254–265.

Metal, D., Sintering, L., & Dmls, T. (n.d.). Application Notes Design Rules for DMLS, *49*, 1–14.

Moammer, A. A. (2011). *Thermal Management of Moulds and Dies – A Contribution to Improved Design and Manufacture of Tooling for Injection Moulding*.

Mrozek, K., & Mierzwiczak, M. (2015). Application of the method of fundamental solutions to the analysis of fully developed laminar flow and heat transfer. *Journal of Theoretical and Applied Mechanics*, *53*, 505–518.

Ning, Y., Wong, Y. S., Fuh, J. Y. H., & Loh, H. T. (2006). An approach to minimize build errors in direct metal laser sintering. *Automation Science and Engineering, IEEE Transactions On*, *3*, 73–80.

NingYu. (2005). Process Parameter Optimization for Direct Metal Laser Sintering (DMLS) . *PHD Thesis*.

Ö. Poyraz, E. Yasa, G. Akbulut, A.Orhangü, S. P. (2015). Investigation of support structures for direct metal laser sintering (DMLS) of IN625 parts. *Internation Solid Free Form Fabrication Symposium*, 560–574.

O Gloinn, T., Hayes, C., Hanniffy, P., & Vaugh, K. (2007). FEA simulation of conformal cooling within injection moulds. *International Journal of Manufacturing Research*, *2*, 162–170.

Oktem, H., Erzurumlu, T., & Uzman, I. (2007). Application of Taguchi optimization technique in determining plastic injection molding process parameters for a thin-shell part. *Materials and Design*.

Olakanmi, E. O. (2013). Selective laser sintering/melting (SLS/SLM) of pure Al, Al–Mg, and Al–Si powders: Effect of processing conditions and powder properties. *Journal of Materials Processing Technology*, *213*, 1387–1405.

Osswald, T. A., Turng, L.-S., & Gramann, P. J. (2008). *Injection molding handbook*. Hanser Verlag.

Ozcelik, B., & Erzurumlu, T. (2006). Comparison of the warpage optimization in the plastic injection molding using ANOVA, neural network model and genetic algorithm. *Journal of Materials Processing Technology*, *171*, 437–445.

Park, H.-S., & Dang, X.-P. (2010). Optimization of conformal cooling channels with array of baffles for plastic injection mold. *International Journal of Precision Engineering and Manufacturing*, *11*, 879–890.

Park, H.-S., & Pham, N. H. (2009). Design of conformal cooling channels for an automotive part. *International Journal of Automotive Technology*, *10*, 87–93.

Raghunath, N., & Pandey, P. M. (2007). Improving accuracy through shrinkage modelling by using Taguchi method in selective laser sintering. *International Journal of Machine Tools and Manufacture*, *47*, 985–995.

Rahim, S. Z. A. (2015). Performance Evaluation Of Conformal And Straight Cooling Channels On Injection Moulded Part Shayfull Zamree Abd Rahim Universiti Teknologi Malaysia.

Rännar, L., Glad, A., & Gustafson, C. (2007). Efficient cooling with tool inserts manufactured by electron beam melting. *Rapid Prototyping Journal*, *13*, 128–135.

Rigelsford, J. (2003). Injection Molding Handbook. 3/e. *Assembly Automation*, *23*.

Rout, S. K., Mishra, D. P., Nath Thatoi, D., & Acharya, A. K. (2012). Numerical analysis of mixed convection through an internally finned tube. *Advances in Mechanical Engineering*.

Sachs, E., Wylonis, E., Allen, S., Cima, M., & Gu, H. (2000). Production of Injection

Molding Tooling With Conformal Cooling Channels Using the Three Dimensional Printing Process. *Polymer Engineering and Science*, *40*, 1232–1247.

Saifullah, A. (2011). An Investigation on Warpage Analysis in Plastic Injection Moulding. *Advanced Materials Research*, *264*, 433–438.

Saifullah, A. B. M. (2011a). *AN INVESTIGATION ON CONFORMAL COOLING IN PLASTIC INJECTION MOULDING*. Swinburne University of Technology.

Saifullah, A. B. M. (2011b). *AN INVESTIGATION ON CONFORMAL COOLING IN PLASTIC INJECTION MOULDING*. Swinburne University of Technology.

Saifullah, A. B. M., & Masood, S. H. (2007a). Cycle time reduction in injection moulding with conformal cooling channels. *Conference Proceedings of the International Conference on Mechanical Engineering*, *2007*, 29–31.

Saifullah, A. B. M., & Masood, S. H. (2007b). Cycle time reduction in injection moulding with conformal cooling channels. In *Conference Proceedings of the International Conference on Mechanical Engineering* (pp. 29–31).

Saifullah, A. B. M., & Masood, S. H. (2007c). Finite Element Thermal Analysis of Conformal Cooling Channels in Injection Moulding. *Australasian Congress on Applied Mechanics, ACAM*, 1–5.

Saifullah, A. B. M., Masood, S. H., & Sbarski, I. (2009). New cooling channel design for injection moulding. In *Proceedings of the World Congress on Engineering* (Vol. 1).

Saifullah, A. B. M., Masood, S. H., & Sbarski, I. (2012). Thermal–structural analysis of bi-metallic conformal cooling for injection moulds. *The International Journal of Advanced Manufacturing Technology*, *62*, 123–133.

Saifullah, A., & Masood, S. H. (2007a). Optimum cooling channels design and Thermal analysis of an Injection moulded plastic part mould. *Materials Science Forum*, *561*, 1999–2002.

Saifullah, A., & Masood, S. H. (2007b). Optimum cooling channels design and Thermal analysis of an Injection moulded plastic part mould. In *Materials Science*

*Forum* (Vol. 561, pp. 1999–2002). Trans Tech Publ.

Sánchez, R., Aisa, J., Martinez, A., & Mercado, D. (2012). On the relationship between cooling setup and warpage in injection molding. *Measurement: Journal of the International Measurement Confederation*, *45*, 1051–1056.

Shah, R. K., & Sekulić, D. P. (2003). Fundamentals of Heat Exchanger Design. In *... to Thermo-Fluids Systems Design*.

Shayfull, Z., Sharif, S., MohdZain, A., MohdSaad, R., & Fairuz, M. a. (2013). Milled Groove Square Shape Conformal Cooling Channels in Injection Moulding Process. *Materials and Manufacturing Processes*, *28*, 884–891.

Shayfull, Z., Sharif, S., Zain, A. M., Nasir, S. M., & Mohd Saad, R. (2015). Improving the Quality and Productivity of Molded Parts with a New Design of Conformal Cooling Channels for the Injection Molding Process. *Advances in Polymer Technology*.

Shen, C., Wang, L., Cao, W., & Qian, L. (2007). Investigation of the Effect of Molding Variables on Sink Marks of Plastic Injection Molded Parts Using Taguchi DOE Technique. *Polymer-Plastics Technology and Engineering*, *46*, 219–225.

Shie, J.-R. (2008). Optimization of injection-molding process for mechanical properties of polypropylene components via a generalized regression neural network. *Polymers For Advanced Technologies*, *19*, 73–83.

Shinde, M. S., & Ashtankar, K. M. (2017). Additive manufacturing–assisted conformal cooling channels in mold manufacturing processes. *Advances in Mechanical Engineering*, *9*.

Shoemaker, J. (2006). Moldflow design guide.

Shuaib, N. A., Fathullah, M., Shayfull, Z., Nasir, S. M., & Hamzas, M. (2014). Warpage analysis between straight and conformal cooling channels on thin shallow shell. *Key Engineering Materials*, *594*, 676–685.

Spierings, A. B., Schneider, M., & Eggenberger, R. (2011). Comparison of density measurement techniques for additive manufactured metallic parts. *Rapid Prototyping Journal*, *17*, 380–386.

Sun, Y. F., Lee, K. S., & Nee, A. Y. C. (2004). Design and FEM analysis of the milled groove insert method for cooling of plastic injection moulds. *The International Journal of Advanced Manufacturing Technology*, *24*, 715–726.

Tang, L. Q., Chassapis, C., & Manoochehri, S. (1997). Optimal cooling system design for multi-cavity injection molding. *Finite Elements in Analysis and Design*, *26*, 229–251.

Tang, S. H., Kong, Y. M., Sapuan, S. M., Samin, R., & Sulaiman, S. (2006). Design and thermal analysis of plastic injection mould. *Journal of Materials Processing Technology*, *171*, 259–267.

Thomas, D. (2009). The Development of Design Rules for Selective Laser Melting. *Ph.D Thesis, University of Wales, Cardiff*.

Titomanlio, G., & Jansen, K. M. B. (1996). In-mold shrinkage and stress prediction in injection molding. *Polymer Engineering and Science*.

Tsopanos, S., Sutcliffe, C. J., & Owen, I. (2005). The Manufacture of Micro Cross-Flow Heat Exchangers by Selective Laser Melting. *Proc. of the 5th Int. Conference on Enhanced, Compact and Ultra-Compact Heat Exchangers: Science, Engineering and Technology*, 410–417.

Vandenbroucke, B., & Kruth, J. (2007). Selective laser melting of biocompatible metals for rapid manufacturing of medical parts. *Rapid Prototyping Journal*, *13*, 196–203.

Venkatesh, G., & Ravi Kumar, Y. (2017). Thermal Analysis for Conformal Cooling Channel. *Materials Today: Proceedings*, *4*, 2592–2598.

Wang, C.-C., Chi, K.-Y., & Chang, C.-J. (2000). Heat transfer and friction characteristics of plain fin-and-tube heat exchangers, part II: Correlation. *International Journal of Heat and Mass Transfer*, *43*, 2693–2700.

Wang, T.-H., & Young, W.-B. (2005). Study on residual stresses of thin-walled injection molding. *European Polymer Journal*, *41*, 2511–2517.

Wang, Y. qi, Kim, J. gyu, & Song, J. il. (2014). Optimization of plastic injection molding process parameters for manufacturing a brake booster valve body.

*Materials and Design*, *56*, 313–317.

Wang, Y., Yu, K.-M., & Wang, C. C. L. (2015). Spiral and conformal cooling in plastic injection molding. *Computer-Aided Design*, *63*, 1–11.

Wohlers, T. (2009). Wohlers Report 2009 Rapid Prototyping, Tooling & Manufacturing State of the Industry Wohlers Associates. *Inc., Fort Collins, Colorado, USA.*

Xu, X., Sachs, E., & Allen, S. (2001). The design of conformal cooling channels in injection molding tooling. *Polymer Engineering and Science*, *41*, 1265.

Yap, C. Y., Chua, C. K., Dong, Z. L., Liu, Z. H., Zhang, D. Q., Loh, L. E., & Sing, S. L. (2015). Review of selective laser melting: Materials and applications. *Applied Physics Reviews*.

Yasa, E., & Kruth, J. P. (2011). Microstructural investigation of selective laser melting 316L stainless steel parts exposed to laser re-melting. *Procedia Engineering*, *19*, 389–395.

Yeo, W. L., Saw, W. S., & Lai, K. C. (2017). Ribbed Flat-plate Heat sink : Design and Optimization.

Zhang, D., Cai, Q., Liu, J., & Li, R. (2011). Research on process and microstructure formation of W-Ni-Fe alloy fabricated by Selective Laser melting. *Journal of Materials Engineering and Performance*, *20*, 1049–1054.